National Aeronautics and Space Administration

Detailed Design of a Magnetically-Geared Actuator for use in Extremely Cold Lunar Environments

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Motivation

- Rotational actuators for Space mechanisms require a mechanical gearbox to meet mass, volume requirements
- Mechanical gears require lubrication to achieve satisfactory performance & life
- SOA approaches for temperatures < about -60 ºC**:**

Current approaches	**Current penalty**
Heat the gearbox/motor to ≥ -60 °C & use grease lubrication	Increased complexity & mass less power for science
Use dry film lubricant on contacting surfaces	(often significant) reductions in life design constraints on load & speed

- **This is a pervasive problem** – *potential for big impact*

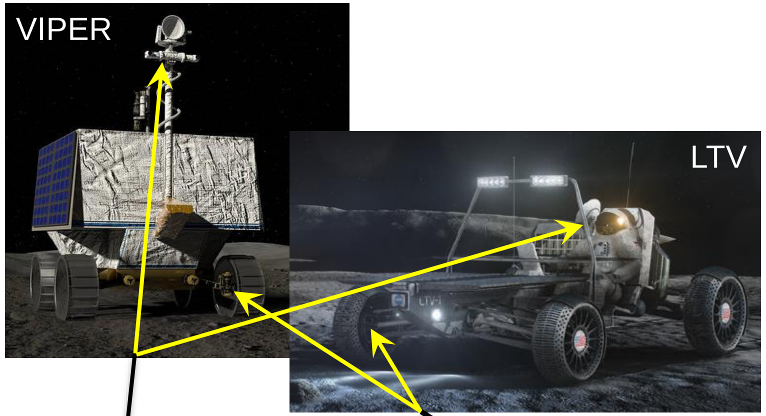
Mechanisms affected
Rover wheels
Solar arrays
Gimbals
ISRU (drills, buckets, etc)
Robot arms
…

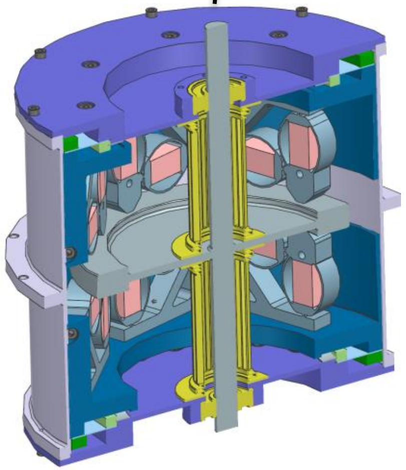
Environments affected
Lunar surface
Lunar Gateway
Mars
Europa
Titan
…

Motors for Dusty & Extremely Cold Environments (MDECE) Project

- **R&D & ground test project, Oct 2020 – Sep 2024**
- **Goal:** Develop 2 <u>unheated</u> rotational actuators that can operate for a <u>long duration in extreme cold</u> (ambient temperature of -243 ºC (30 K))
  - Evaluate life in controlled, representative lunar dust environment with and without lunar simulant
- **Approach:** Eliminate gear lubrication – 1 actuator with non-contact gearing, 1 actuator with no gears
- **Key Performance Parameters:** Min. operating temperature ▪ dust-free life ▪ efficiency of magnetic actuator ▪ output resolution of piezoelectric actuator
- **Relevant environment:** Broadly applicable; focusing on lunar PSR
- **Promising applications:**
  - <u>Magnetic actuator</u>: rover mobility ▪ in-situ resource utilization ▪ robotic arm joints ▪ rotors for powered flight
  - <u>Piezoelectric actuator</u>: precision pointing (e.g., laser communication) ▪ low power robotic arm joints

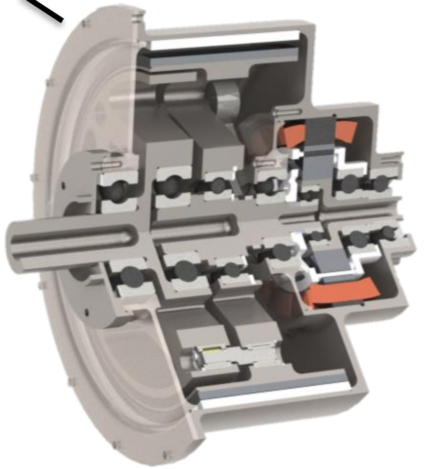
Example mechanisms for demonstrating prototypes (NASA KSC)





Piezoelectric actuator preliminary design (JPL)

[graphic courtesy of NDEAA team / JPL / Caltech / NASA (Patent pending)]



Magnetically-geared actuator preliminary design (NASA GRC & GSFC)

Driving Requirements

Mechanical output
- Continuous 105 Nm at 2 rpm (22 W power)
- Peak 208 Nm at up to 1.5 rpm (up to 33 W) for 20+ seconds

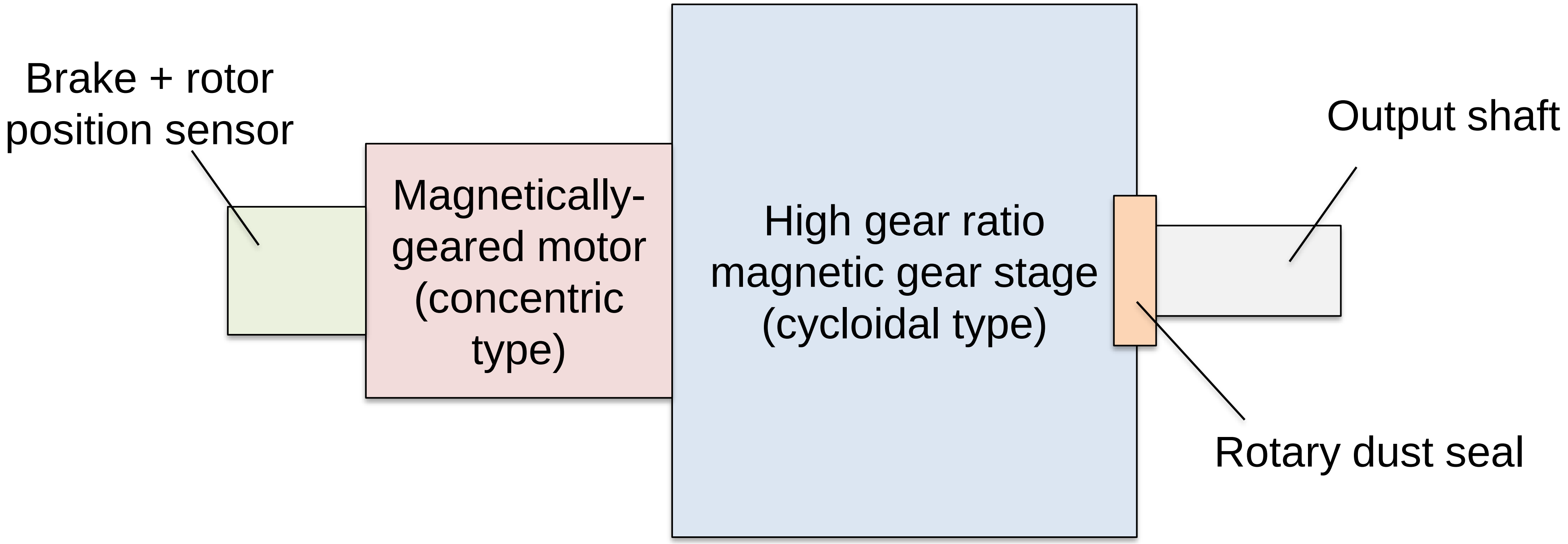
Match flight-qualified reference actuator

Size / mass
- No strict requirements (TRL 2-5)
- Mass 4.73 kg (max), < 3.15 kg (goal)
- Envelope volume 1440 cm^3 (max), < 960 cm^3 (goal)
- Aspect ratio (L/D) 0.5 to 1.75

Thermal specifications

Parameter	Condition	Specification			
		Minimum		Maximum	
		Goal	Required	Required	Goal
Lunar surface temperature	Operating	30 K (-243 °C)	108 K (-165 °C)	293 K (20 °C)	313 K (40 °C)
	Survival	3 K (-270 °C)	108 K (-165 °C)	293 K (20 °C)	393 K (120 °C)
Solar heating environment	Operating	Shadowed	Shadowed	N/A	Lunar south pole (85° S)
	Survival	Shadowed	Shadowed	N/A	Lunar equator

MDECE Magnetic Actuator Configuration

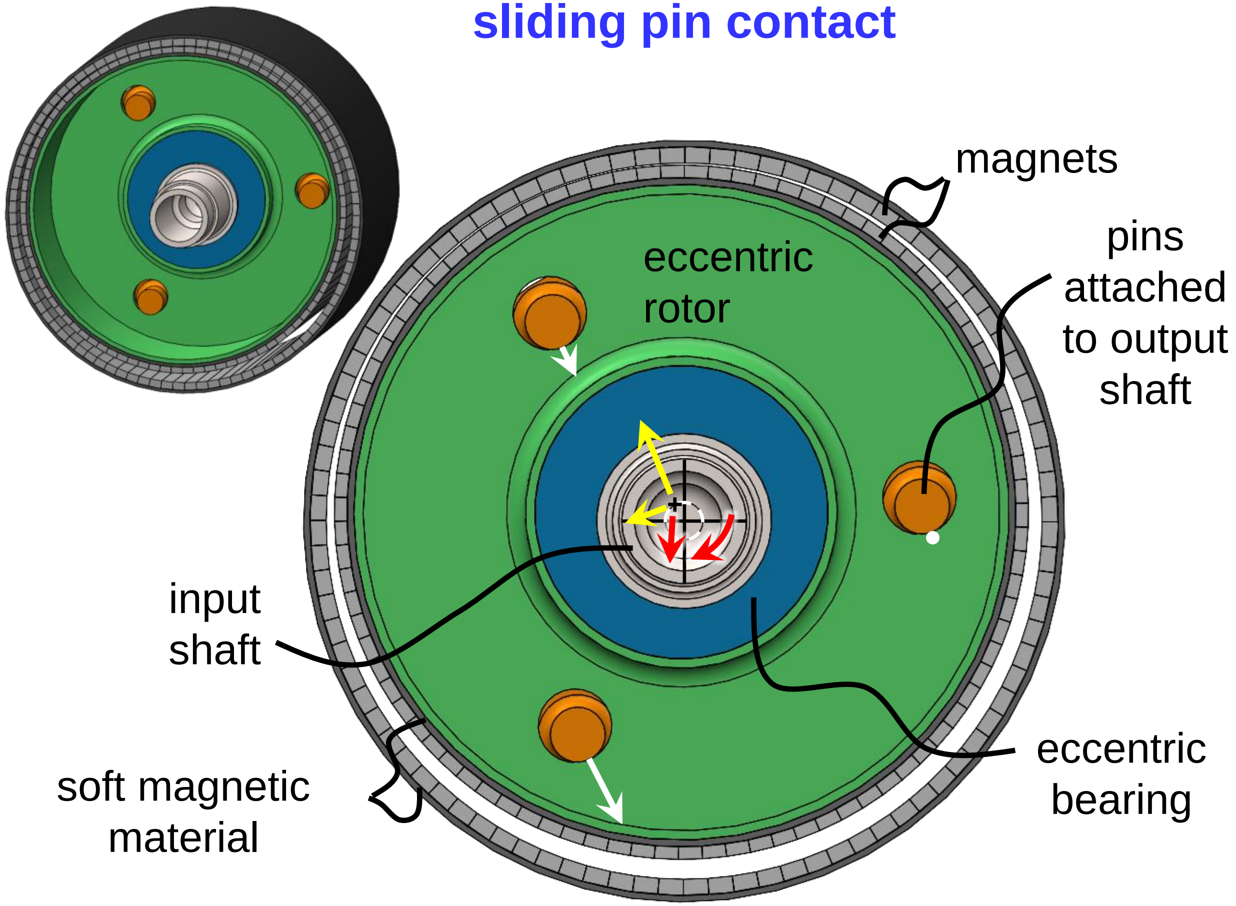


- Magnetic components of both cycloidal gear and magnetically-geared motor designed using genetic optimizations based on static 2D finite element analysis
- Selected 0.25 mm nominal gap for both

Initial Electromagnetic Design

- Eccentricity of eccentric rotor is major driver of cycloidal gear's mass & size
  - Causes large bearing forces
- Output torque must transfer through connection that has opposite eccentricity
  - 2 options evaluated for the connection: sliding pins & needle bearings

Example cycloidal magnetic gear with sliding pin contact

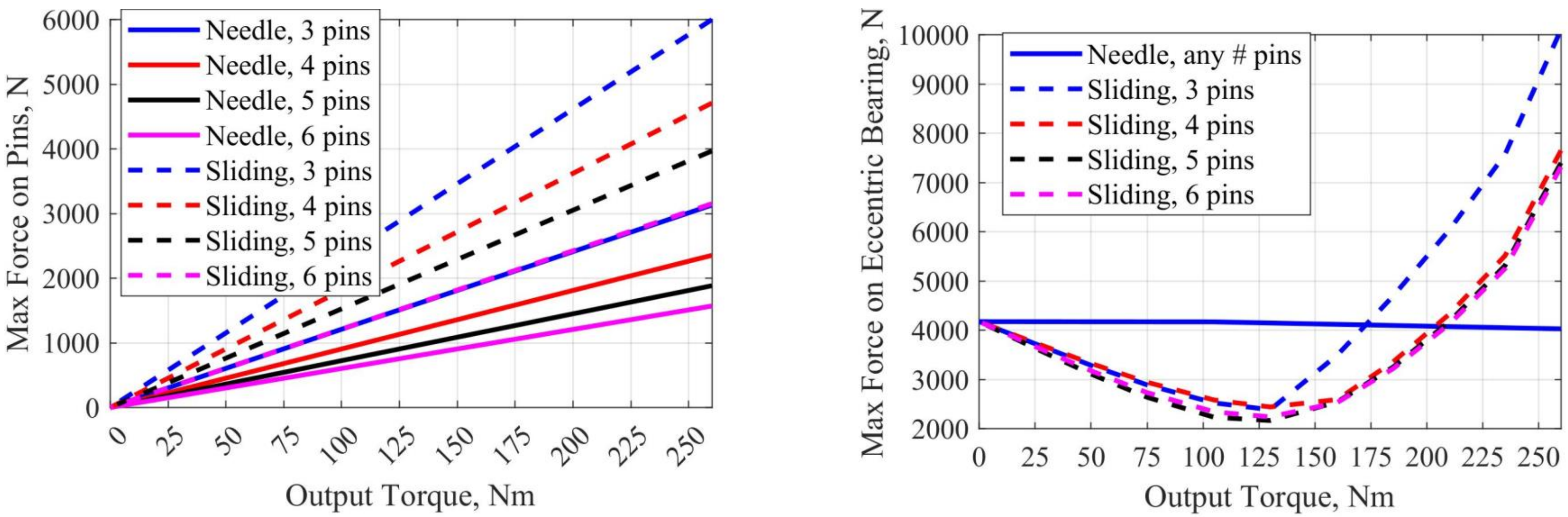


- Pin-to-rotor contact force
- Load through eccentric bearing
- Net radial magnetic force & torque on eccentric rotor

Initial Electromagnetic Design

- Increasing # of pins reduces peak pin force (thus bearing forces), but with diminishing returns & at expense of complexity and eventually mass [*left plot below*]
- Sliding pins simpler, but more difficult to keep lubricated & they incur significantly larger bearing force [*right plot below*]
- Magnitude and direction of these forces also time dependent [*see paper*]

Change in max force on pins and eccentric bearing for preliminary cycloidal magnetic gear



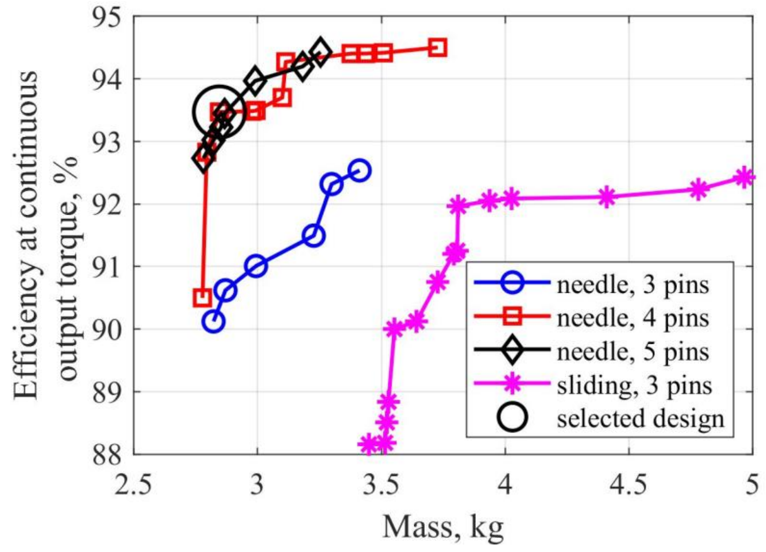
<u>Takeaway</u>**:** Magnitude of pin & bearing forces makes it challenging to balance life of dry film lubricants with size / mass of bearings

Initial Electromagnetic Design

- Selected cycloidal gear**:** 4 pins, needle bearings, 43:1 gear ratio
  - Mass**:** 2.85 kg
  - Continuous efficiency**:** 91.9%

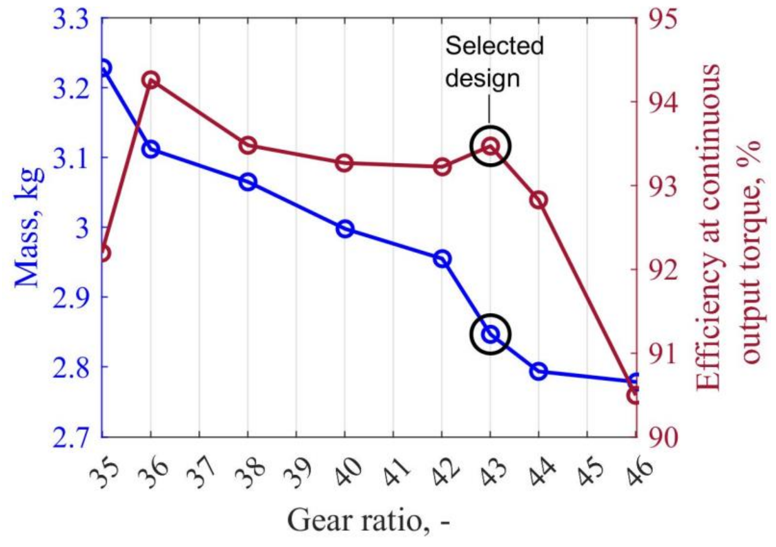
- Selected geared-motor**:** 13.5:1 gear ratio
  - Mass**:** 0.89 kg
  - Continuous efficiency**:** 91.3%

Pareto fronts from genetic optimization of cycloidal gear

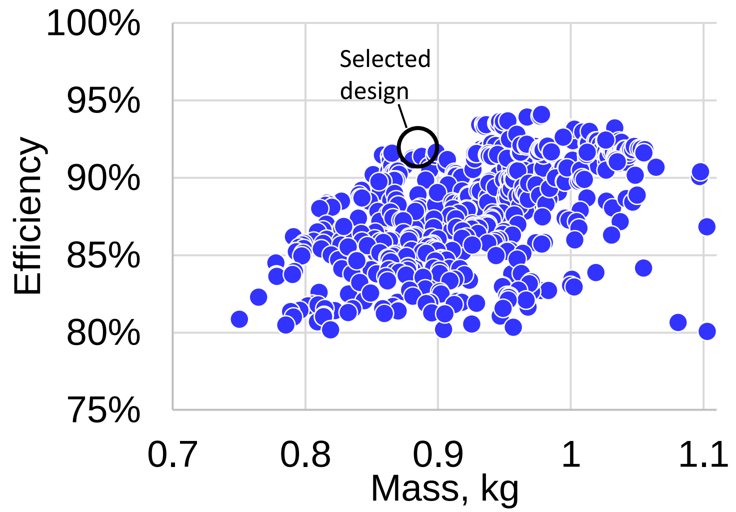


Optimal mass & efficiency of cycloidal as function of gear ratio

(4 pins, needle bearings)



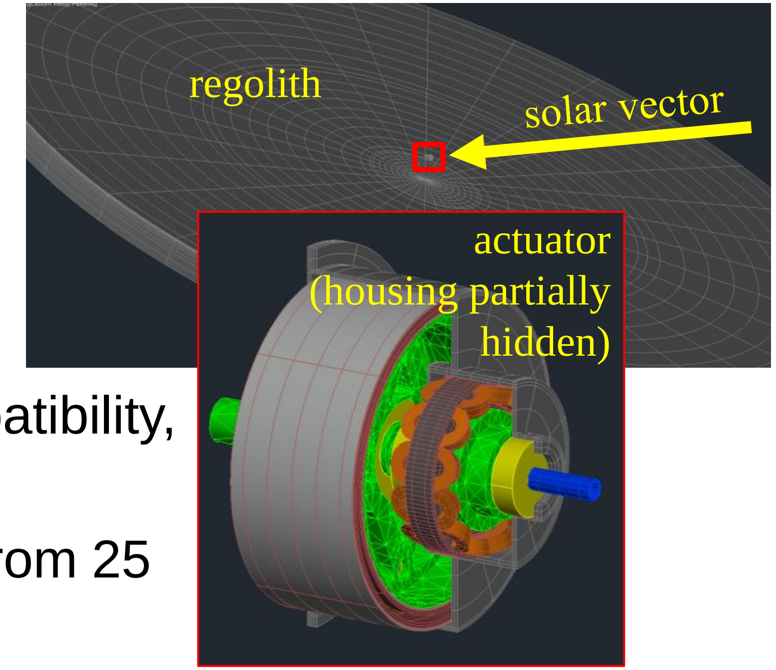
Genetic optimization of magnetically-geared motor

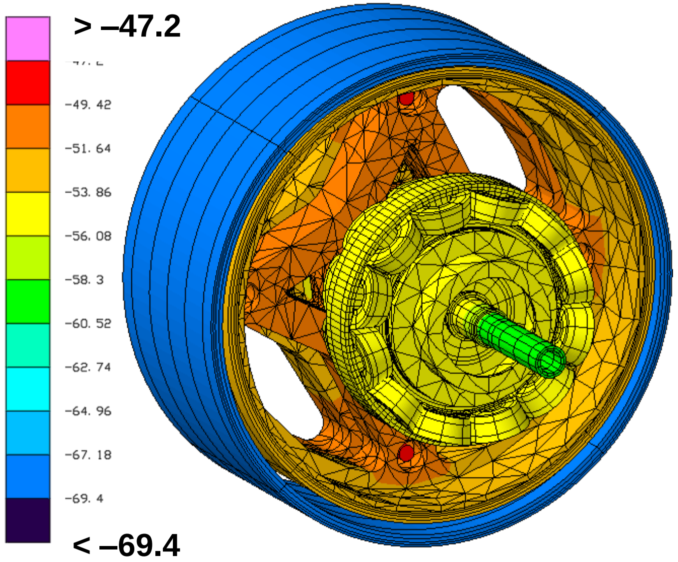


Takeaway**:** Sliding pins found to be less efficient and considerably heavier than needle bearings

Thermal Analysis

- 3D finite element model of actuator and lunar surface
- Temperature-dependent material properties included where available
- At this time, needle bearing loss very conservative (3X prediction for grease lubrication)
- Generic anodized titanium finish on housing selected due to cryo compatibility, relatively high emissivity, & relatively low absorptivity-to-emissivity ratio
- Across operating environments, internal actuator temperature ranges from 25 K (-248 ºC) to about 393 K (120 ºC)





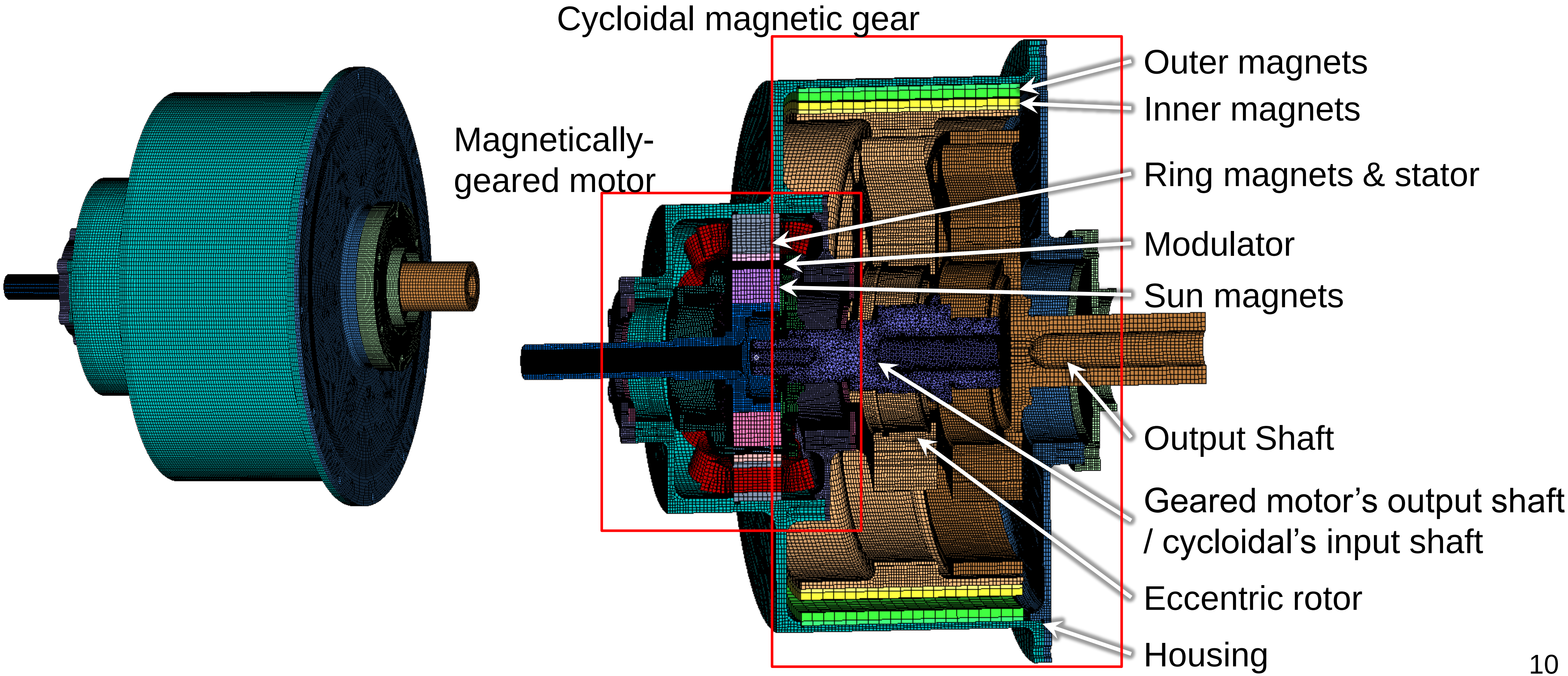
Steady-state response of preliminary actuator in cold operating goal environment under continuous operation

<u>Takeaways</u>:

- Temperature rise during 20 second peak operation is small (~2 ºC)
- Temperature gradients across bearings & air gaps are up to 19 ºC but typically < 7 ºC

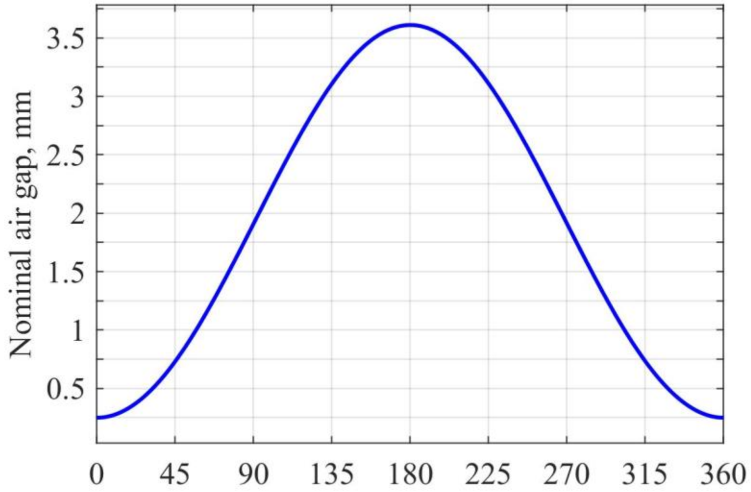
Structural Analysis

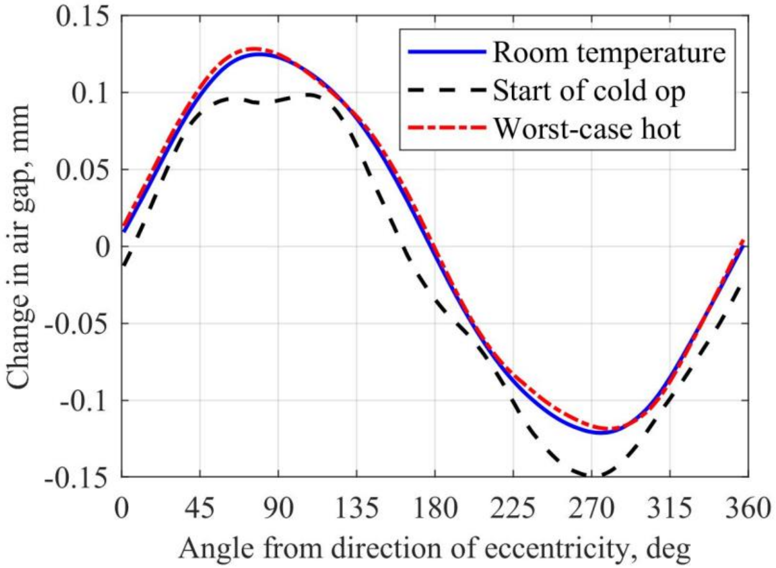
- Forces included**:** thermal, magnetic (radial and torsional), centrifugal
- Static thermal conditions**:** room temperature, worst-case cold operation, worst-case hot operation



Structural Analysis

Nominal air gap in the cycloidal gear (top) and deviation in air gap caused by structural deformation at peak output torque (bottom)





Predicted life of dry film lubricated bearings in preliminary design

	Bearing							
	1	2	3	4	5	6	7-14	15
Revolutions (millions)	8.7	8.8	25.7	0.56	0.18	0.44	0.41	0.44
% of threshold	250	273	796	217	68	167	159	7333
% of goal	30	33	96	26	8	20	19	880

Takeaways:

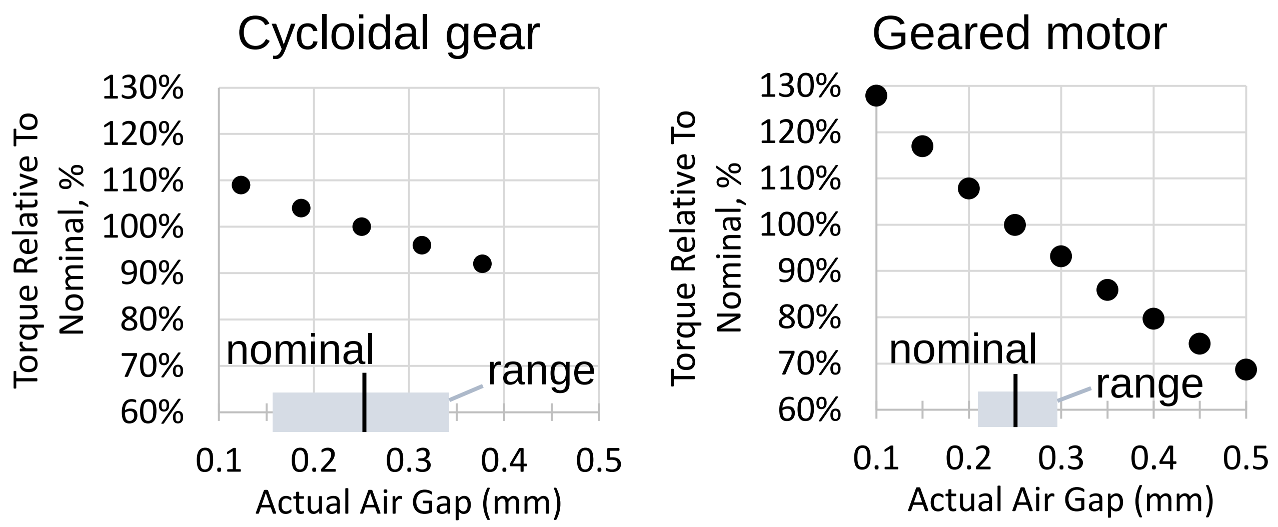
- Under peak load, structural deformation of air gap is significant but only away from location of minimum nominal gap
- Threshold life nearly achievable with selected bearings, but design modifications required to approach goal life

Additional Electromagnetic Analysis

- 3D electromagnetic analysis of torque capacity
  - Magnetically-geared motor**:** 3D effects large (24% torque reduction relative to 2D model), but accurately captured by motor design code
  - Cycloidal gear**:** 3D effects only 1% for baseline design and only up to 3.2% to 5.5% if number of eccentric rotors increased to 2 or 3 to reduce bearing loads

Influence of air gap on predicted torque

(expected range of air gap & nominal value shown)



Impact of replacing iron in cycloidal gear with air or extra magnet on actuator's output torque (T) and approximate total mass (m)

		Eccentric rotor		
		No iron	**Baseline (iron)**	**Magnet**
Housing	**No iron**	T: –0.6% m: –11.3%	T: –0.1% m: –6.2%	-
	Baseline (iron)	T: –0.7% m: –5.1%	0%	T: +18.5% m: –1.2%
	Magnet	-	T: +15.9% m: –1.0%	T: +37.6% m: –2.5%

Summary & Future Work

Summary

- Proposed magnetically-geared actuator is viable for lunar surface operation down to 30 K (-243 ºC)
- Material limits are not exceeded at the temperature extremes or peak loads, temperature gradients and differential thermal contractions are manageable, and the expected change in performance over the predicted internal temperature envelope (25 K [-248 ºC] to 430 K [157 ºC]) is acceptably small
- Efficiency of preliminary design (83.9%) is above the project’s efficiency goal
- Mass of preliminary design (5.01 kg) is larger than objective due to challenge of meeting desired bearing life target

Future work

- Proof-of-concept prototype developed in parallel to design work -- assembly finishing end of March, then functionality & performance testing in Earth ambient environment
- Critical design review scheduled for mid-April
    - Design improvement in progress**:** thorough mass optimization ▪ reconfigure cycloidal gear to reduce bearing loads ▪ transient thermal analysis ▪ structural analysis at zero, continuous, and peak torques
- Fully-functional prototype built then ground tested in relevant cryogenic-vacuum-dust environment in 2024

Acknowledgements

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Space Technology Mission Directorate

Game Changing Development Program

MDECE Project

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